Respiratory muscle fatigue: a cause of respiratory failure?

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(Received 26 April 1977; accepted 10 June 1977)

Summary

1. The question whether respiratory muscle fatigue ever causes respiratory failure is over 40 years old, but we still have no definitive answer to this question. Skeletal muscle fatigue occurs when the rate of energy consumption of the muscle is greater than the energy supplied, so that energy stores are utilized and eventually become depleted.

2. Five factors which are important in the development of muscle fatigue (a, the tension developed by the muscle; b, the maximum tension the muscle can develop; c, the energy stored within the muscle; d, the energy supplied to the muscle; e, the efficiency of the muscle). These can be affected in many diseases, so disposing to fatigue, thus respiratory muscle fatigue is likely to be a common occurrence.

3. Respiratory muscle fatigue can in principle easily be diagnosed at the bedside by application of a simple electromyographic technique used to detect fatigue in other skeletal muscles.

Key words: fatigue, muscle, respiratory failure.

Abbreviation: MBC, maximum breathing capacity.

Introduction

Do the respiratory muscles fail in much the same way as the heart fails? The question is at least 42 years old (Killick, 1935) and since then it has been asked time and time again. Skeletal muscle fatigue is not difficult to quantify and it is a phenomenon that has been studied intensively. Thus it is astonishing that very few serious attempts have been made to document respiratory muscle fatigue in either health or disease, in either man or experimental animals. Yet it would appear that we currently have at our disposal all the technology necessary to diagnose and document respiratory muscle fatigue, reliably, non-invasively and before the muscles actually fail as generators of negative intrapleural pressures on inspiration.

Skeletal muscle fatigue (as opposed to central or neuromuscular transmission fatigue) occurs when the rate of energy consumption by a muscle is greater than the rate of energy supplied to the muscle by the blood. That being the case, muscle draws upon its energy stores and when they are depleted the muscle has no further sources of energy and it fails as a pressure generator. Thus when a muscle becomes fatigued its total energy consumption (which equals the total work performed by the muscle divided by its efficiency) is the sum of the energy stores plus the total amount of energy extracted from the blood by the muscle. This can be expressed by a modification of the equation developed by Monod & Scherrer (1965):

\[ \frac{W}{E} = \alpha + \beta t_{\text{lim.}} \]  

where \( W \) = total external work performed by the muscle, \( E \) = efficiency, \( \alpha \) = energy stores, \( \beta \) = rate of energy supplied to the muscle and \( t_{\text{lim.}} \) = endurance time. Solving for \( t_{\text{lim.}} \):
normal subjects can maintain indefinitely. Zocche, Fritts & Cournand (1960) found that normal subjects were capable of maintaining a ventilatory level of 53% of maximum breathing capacity (MBC) for 15 min, and Tenney & Reese (1968) estimated the critical minute ventilation to be 55% of MBC. On the other hand, Shephard (1967) and Leith & Bradley (1976) found that normal subjects could ventilate at 70–80% of MBC for 15 min. The reason for the discrepancy in the various studies is not clear, but could be related to differences in respiratory rate and depth in the different studies. From these studies one could assume values for resistance and compliance and estimate a critical work load in patients that would result in fatigue. Such an exercise would probably not be very useful as more information would be needed about the maximum pressures the patients could develop, the degree of hypoxia, etc. Furthermore, McGregor & Becklake (1961) found that respiratory muscle efficiency decreased markedly as inspiratory resistance was increased for the same external power produced by the respiratory muscles.

Sharp, Van Lith, Vej Nuchprayoon, Briney & Johnson (1968) measured maximum inspiratory mouth pressures in patients with chronic airways obstruction and calculated theoretical values based upon the patients’ lung volumes and the normal values of Rahn et al. (1946). Their measured values were \( -1.5-6.0 \text{ kPa} \) \((-15-60 \text{ cm water})\) [mean, \(-3.0 \text{ kPa}\) \((-30 \text{ cm water})\)] whereas the calculated values ranged from zero to \(-6.4 \text{ kPa} \) \((-64 \text{ cm water})\) [mean, \(-39 \text{ kPa}\) \((-39 \text{ cm water})\)]. Our studies indicate that the critical transdiaphragmatic pressure above which fatigue occurs is 40% of maximum (Roussos & Macklem, 1977). For all the inspiratory muscles acting together we estimated the critical pressure to be between 50 and 70% of maximum (Roussos, Fixley, Gross & Macklem, 1976). Combining the two estimates would indicate that the critical inspiratory transpulmonary pressure swings in airways obstruction would be in the order of 2.0 kPa (20 cm water), a value that is very likely to be exceeded during exercise in such patients, and also during a severe attack of asthma. Sharp et al. (1968) concluded that ‘...ineffectiveness or exhaustion of inspiratory muscles, working at disadvantageously short initial lengths ...’ might be a major factor in the
development of hypercapnia and that ‘... failure of the inspiratory pump may be an important contributing factor in their ventilatory failure’. Although hyperinflation may be beneficial in opening obstructed airways, and improving ventilation distribution and gas exchange, it is hardly beneficial for inspiratory muscle function.

Our own studies have revealed that when normal subjects are asked to breathe against fatiguing loads at the mouth, they alternate between predominantly using the diaphragm to develop the necessary pressures and using the intercostal/accessory muscles. When the diaphragm is the only inspiratory muscle contracting, the abdomen is displaced outward as the rib cage expands (Goldman & Mead, 1973). When the intercostal/accessory muscles are the only muscles contracting and the transdiaphragmatic pressure remains zero, the abdomen is displaced inwards as the rib cage expands. Thus by simple bedside observation one may determine with a fair degree of accuracy which muscle groups are being used. This may be important. Ashutosh, Gilbert, Anchincloss & Peppi (1975) found that asynchronous breathing movements in patients with obstructive pulmonary disease were associated with a poorer prognosis. Although the asynchrony was complicated, there were inward displacements of the abdomen during inspiration. Similarly, Sharp, Goldberg, Druz, Fishman & Danon (1977) found inward abdominal displacement in inspiration in five of 20 patients not in respiratory failure, but in eight of ten patients who were in respiratory failure, and concluded that there was ‘... growing acceptance of the idea that faulty co-ordination of overworked and fatigued respiratory muscles contributes to dyspnoea and respiratory failure...’.

One can easily think of other situations where inspiratory muscle fatigue is likely to be a cause of respiratory failure. The devastating effects of respiratory infections (which increase the load) in patients with neuromuscular weakness is a good example. Although the exact physiological role of intra-uterine breathing movements remains obscure, they almost certainly play a role in training the respiratory muscles for the day when they must be solely responsible for the act of breathing. Premature babies are born with an inadequate training period. If superimposed upon this, they develop an increased load with the development of the respiratory distress syndrome of infancy, it would not be surprising if inspiratory muscle fatigue was responsible for the hypercapnia that such babies develop. Weaning problems from respirators are not uncommon. Our orthopaedic colleagues tell us that the muscles which atrophy most rapidly when put to rest are those which normally we use the most. The skeletal muscles that we use the most are the respiratory muscles. If they atrophy during prolonged artificial ventilation, is it surprising that some patients during the weaning period can breathe quietly without distress for a short period, but then become progressively more dyspnoeic and the arterial $P_{CO_2}$ starts to climb? In acute pulmonary oedema, there is a decreased cardiac output and hypoxaemia, both of which presumably diminish $\beta$, the rate of energy supply to the muscles. In addition, there is an increase in the work of breathing. Is the hypercapnia sometimes seen in acute pulmonary oedema caused by inspiratory muscle fatigue?

The answer to these questions and the diagnosis of fatigue at the bedside must await the development of a reliable means to detect inspiratory muscle fatigue. Such methods are currently available for other skeletal muscles. Kogi & Hakamada (1962) and Kaiser & Petersén (1963) have shown that with the development of fatigue in a skeletal muscle, the low-frequency components of the electromyogram increase in amplitude while the high-frequency components decrease, for the same tension development. Kogi & Hakamada (1962) showed that the ratio of the two amplitudes (amplitude $<40$ Hz/amplitude $>40$ Hz) was virtually independent of either muscle strength or strength of contraction. When the muscle performed at fatiguing work loads the ratio increased and the increase was apparent before any symptoms of fatigue developed. They used a subjective grading of fatigue. Stage 1 was the appearance of the sensation of fatigue in the muscle. Stage 2 was development of local pain; stage 3 was the desire to relax the contraction and stage 4 was the incapability to maintain tension. There was an excellent correlation between the ratio of the slow- to high-frequency components of the electromyogram and these stages. In stage 1 the ratio increased by 20–40%, in stage 2 by 20–60%; stage 3 by 30–100% and stage 4 by 50–200%. In non-fatiguing loads
there was very little change even though the symptoms of stage I were felt.

The important point to emphasize in this landmark study is that the electromyogram signal of fatigue was easily detectable long before the muscle actually failed as a pressure generator. Attempts have now begun to apply this technique to the detection of inspiratory muscle fatigue. It appears to be suitable in laboratory circumstances in normal subjects (Gross, Grassino & Macklem, 1977). This does not mean that it will be easy to perform in the hustle and bustle of an intensive care ward. However, Swedish investigators have developed this technique to a high degree of sophistication and it is currently being used to detect muscle fatigue in industrial workers on site in their factories (Broman, Magnusson, Petersén & Ortengren, 1973; Lindström, Magnusson & Petersén, 1970; Kadeforze, Petersén & Heberts, 1976; Lindström, Magnusson & Petersén, 1974; Ortengren, 1975). This suggests that the application of this technique to the bedside in hospitals should not be difficult.

We await the results of this development with interest. It should provide the answer to the 40-year-old question: is respiratory muscle fatigue a cause of respiratory failure?

References


